Advances in Satellite Remote Sensing of Earth's atmosphere: Past Present and Future

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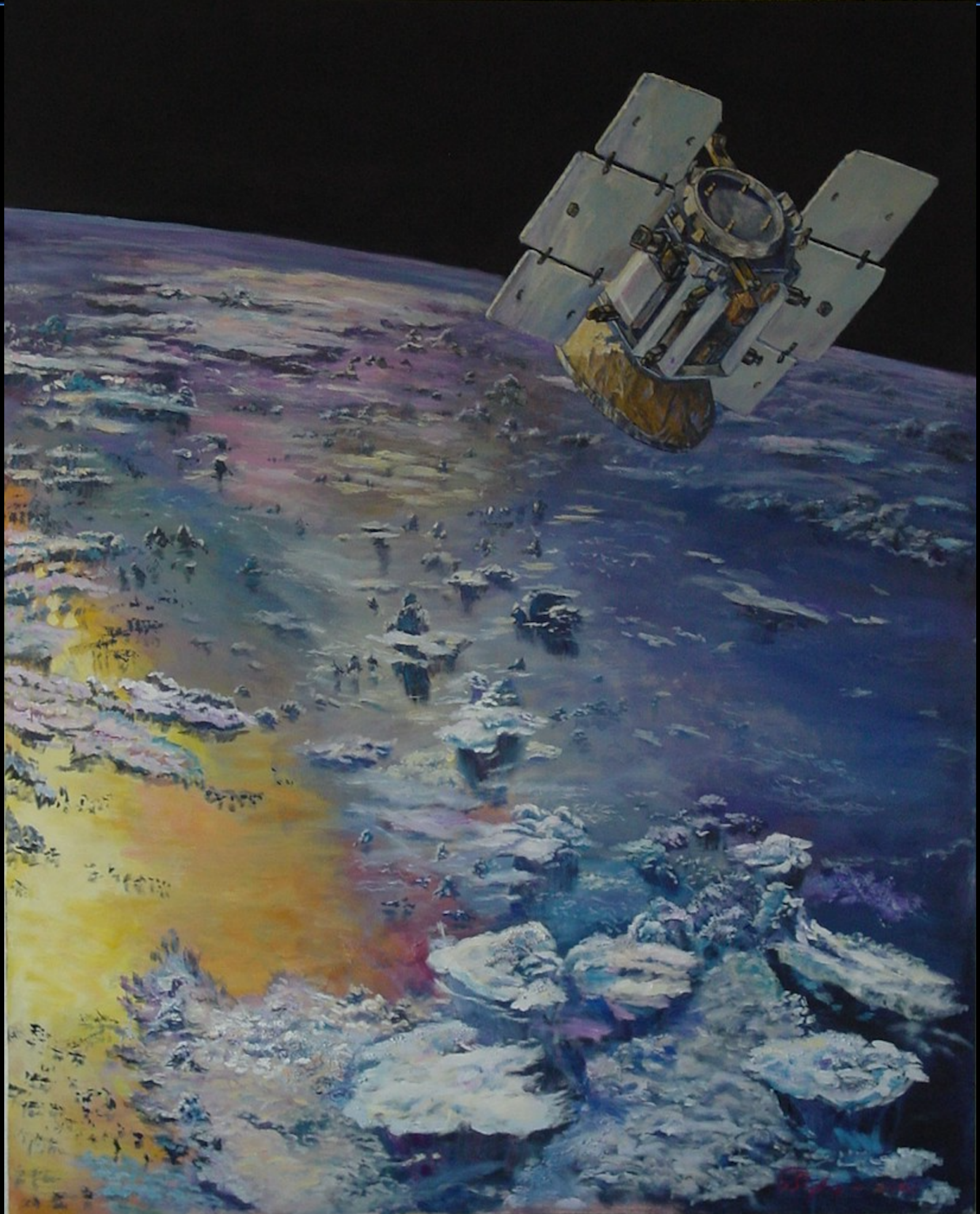

The launch of TIROS-1, April 1960

Chapter 4

Satellites See the World's Atmosphere

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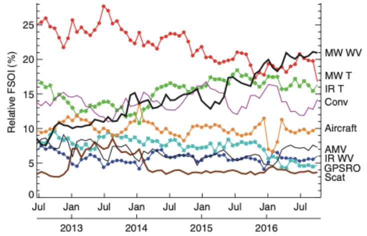
AMS Monograph

ABSTRACT

2000

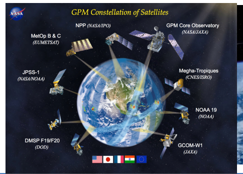
The third phase: grand challenge to create 'knowledge'

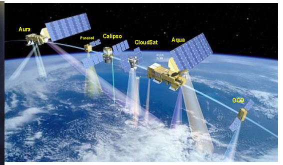


Climate data records

Assimilation of into advance 'analysis systems' to demonstrate impacts on forecasts, applications

Process understanding





Main messages

1) Quantifying the performance of any given satellite remote sensing ‘system’ is complicated, involving many layers of input & influence, often making it difficult to establish.

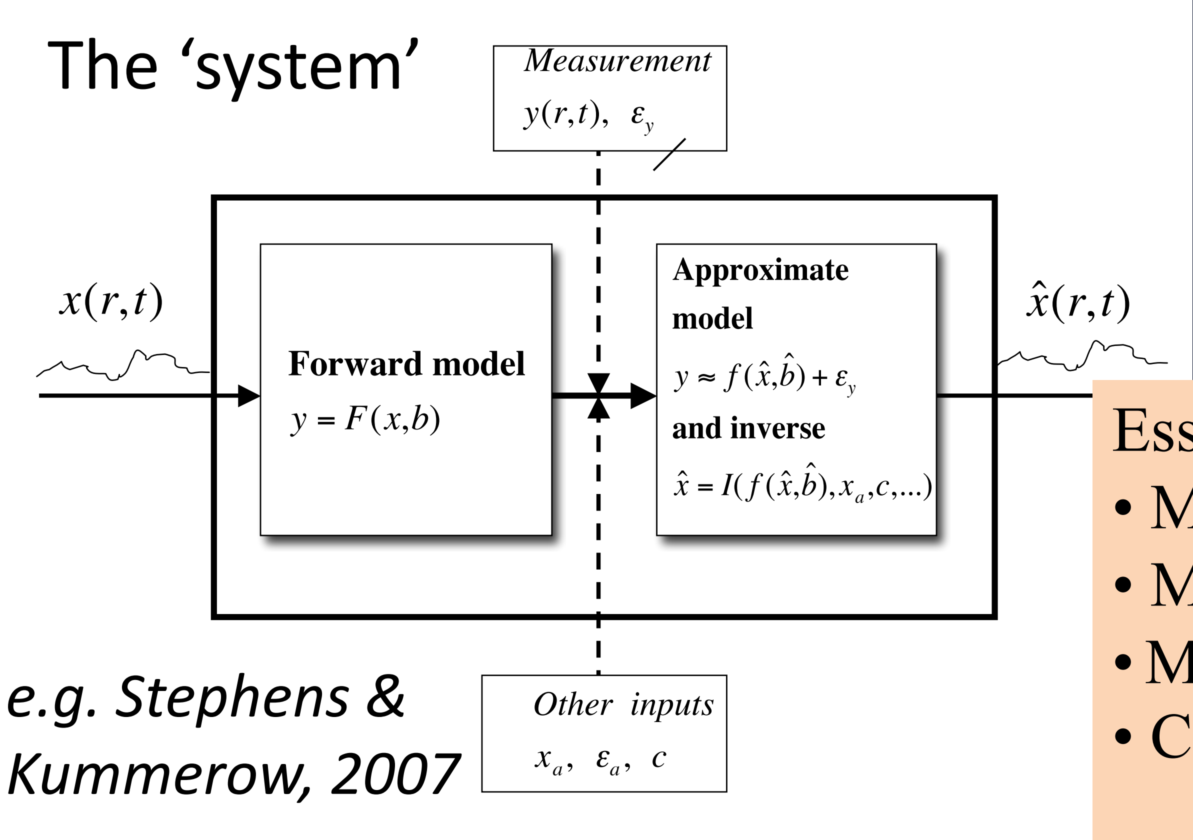
2) We are moving from a more variable centric approach to a more systems approach to observing the Earth system – ie desire for a more integrated observing approach

3) We have made significant progress in designing & using systems that combine different types of observations (& physics) – this has advanced measurements approaches, opened new vistas on processes, & provided new ways to assess old methodologies

4) We are now assembling relatively long records of information, both from operational and research systems, opening new directions of enquiry about Earth system interaction.

5) Today, technologies are rapidly advancing offering new & ‘affordable’ ways to address science and application needs

A remote sensing observing system



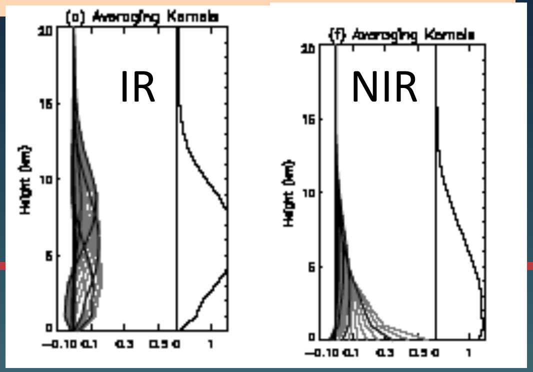
e.g. Stephens & Kummerow, 2007

The overall performance of the 'system' is thus an aggregation of the performances of its many parts.

Essential elements:

- Measurement, y(t) and error ε_y
- Model f & its error ε_f
- Model parameters b and errors
- Constraint parameters c

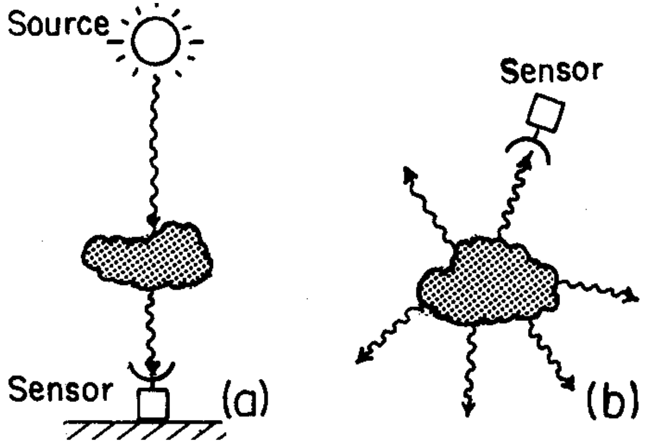
Averaging kernels, information content & propagation



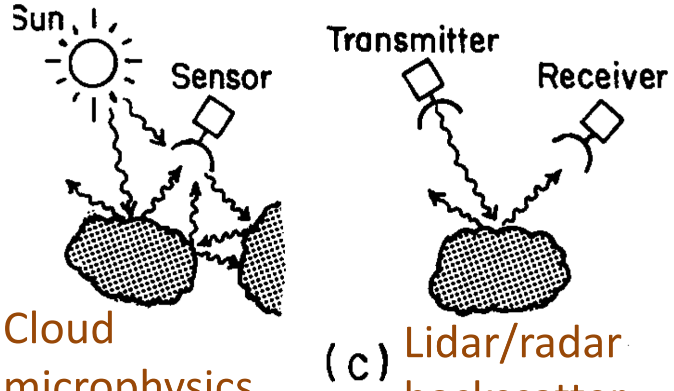
Physics *usually* defines the forward model

Extinction aerosol, composition , …

Emission – sounding, precipitation, cloud water, composition

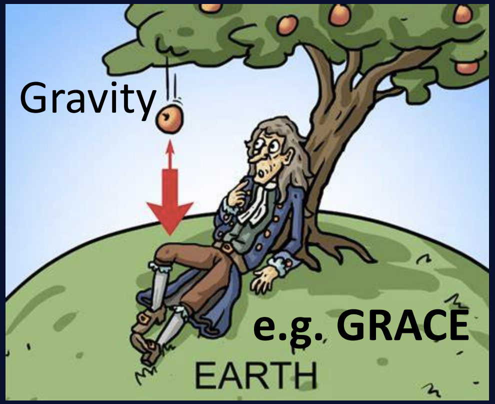


Scattering/reflection- active/passive

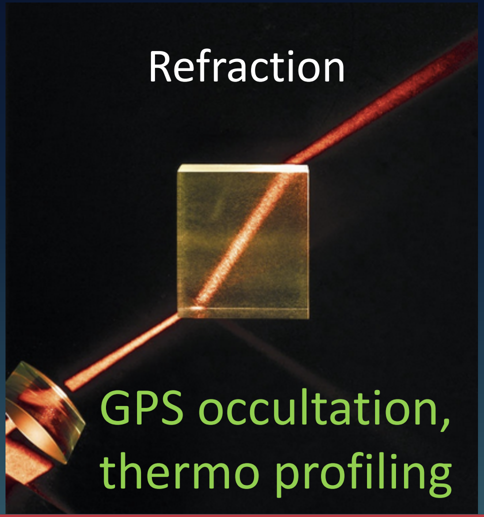


Cloud microphysics, Aerosol, constituents

Lidar/radar backscatter – aerosol, cloud, precipitation



Ice mass change, ocean mass, terrestrial water storage



Passive (radiometry, spectroscopy)

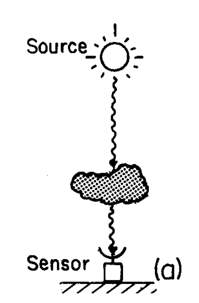
Mostly path integrated information (e.g. optical depths, …). The information derived often contains ambiguities, uncertainties sometimes difficult to quantify

Active (lidar, radar)

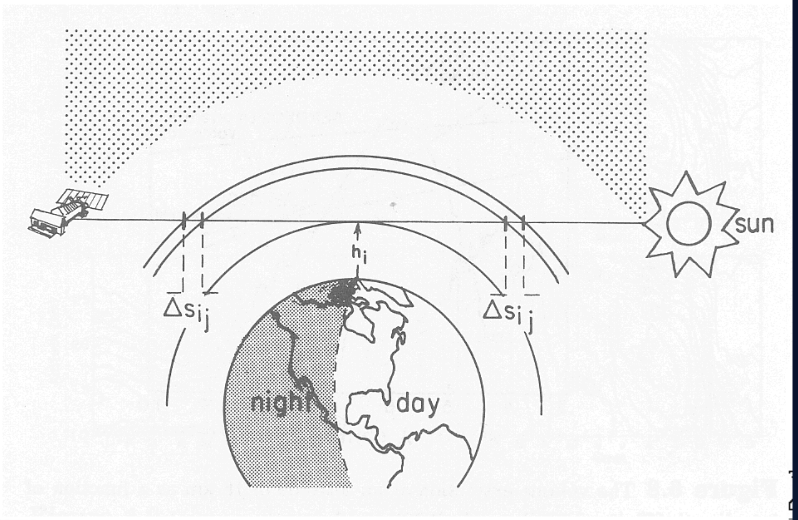
Profile information about occurrence, optical properties, microphysics and bulk water mass, precipitation incidence, this information too is often also ambiguous (e.g. Z-R relationships)

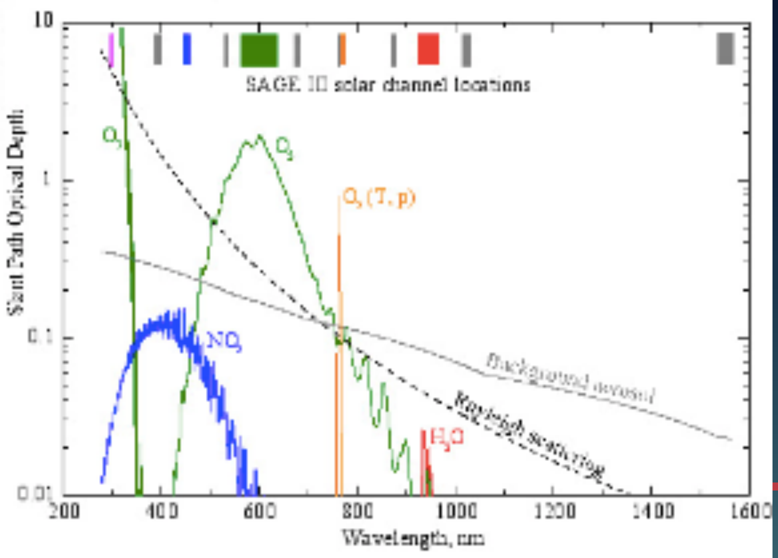
We have & continue to make significant progress in designing & using systems that combine different types of observations (and physics) – such as active with passive

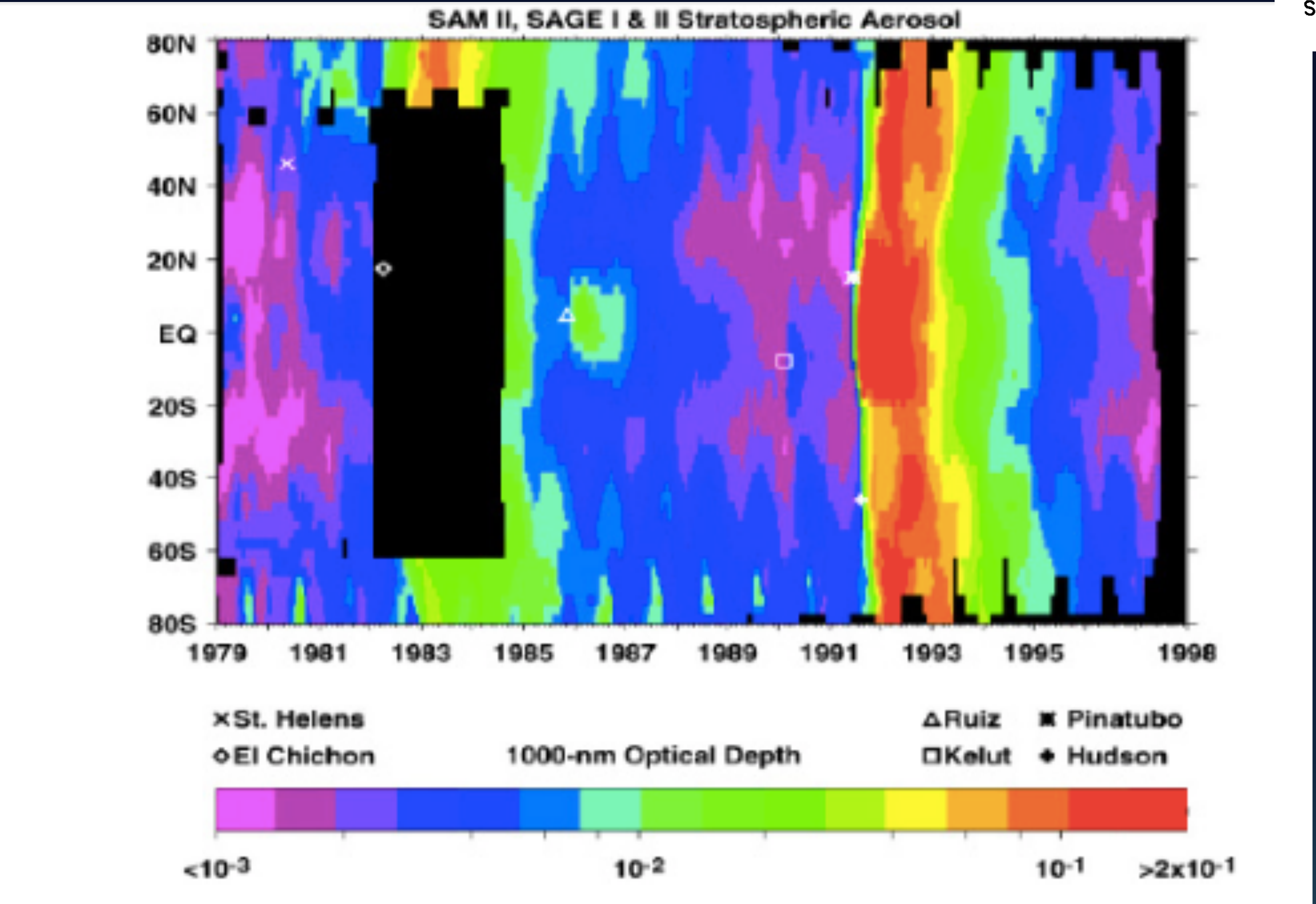
Attenuation - the SAGE example



Extinction from Occultation



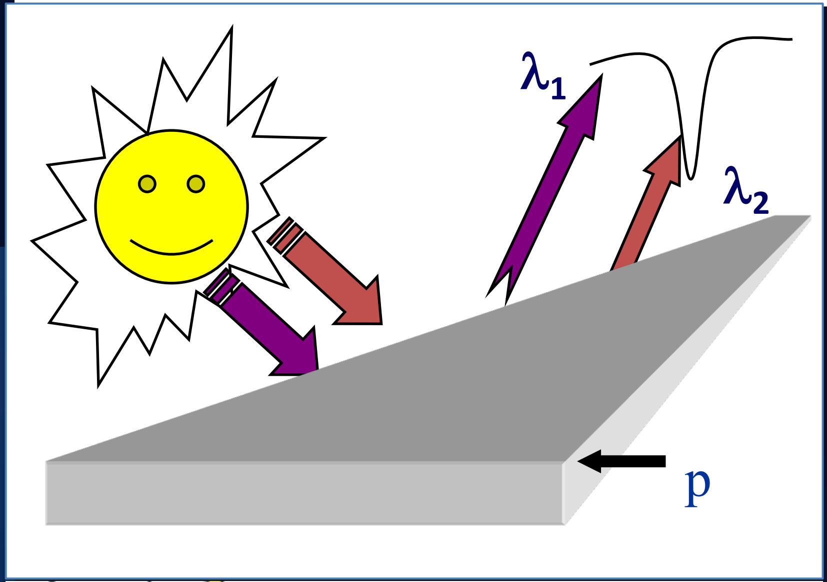


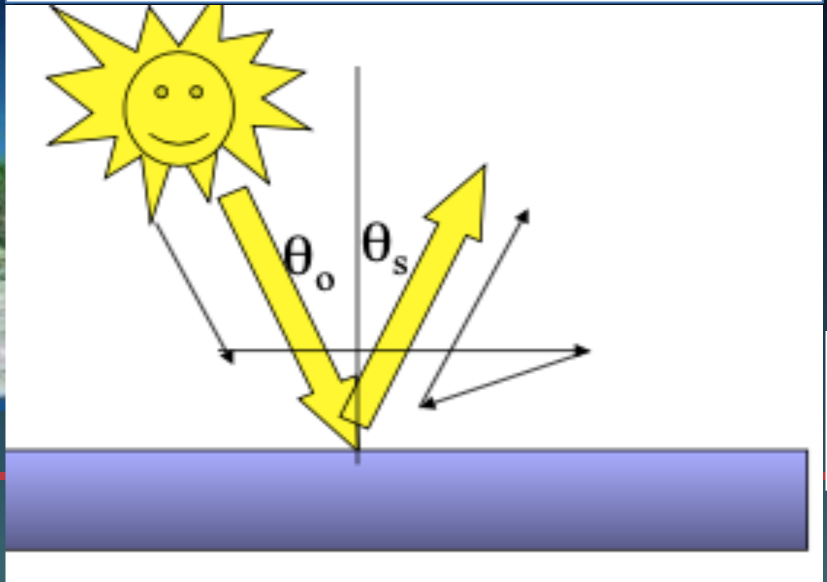


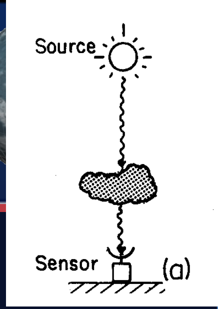
SAGE I first launched Feb 1979
SAGE II

Attenuation - a variation on the theme

Example 1 column CO2, surface pressure







$$I_\nu = I_{o\nu} R_\nu \exp[-\tau_\nu(0, p_s) m]$$

$$m = \frac{1}{\mu_o} + \frac{1}{\mu_s}$$

$$\mu_{o/s} = \cos\theta_{o/s}$$

The forward model

As a simple ratio, and provided wavelengths are close enough, surface reflection ~ same

$$\frac{I_{\nu 1}}{I_{\nu 2}} = \frac{I_{o\nu 1}}{I_{o\nu 2}} \frac{R_{\nu 1}}{R_{\nu 2}} \exp[-(t_1(p_s) - t_2(p_s))m]$$

$$X = \ln\left[\frac{I_{\nu 1}}{I_{\nu 2}}\right] = -(t_1(p_s) - t_2(p_s))m$$

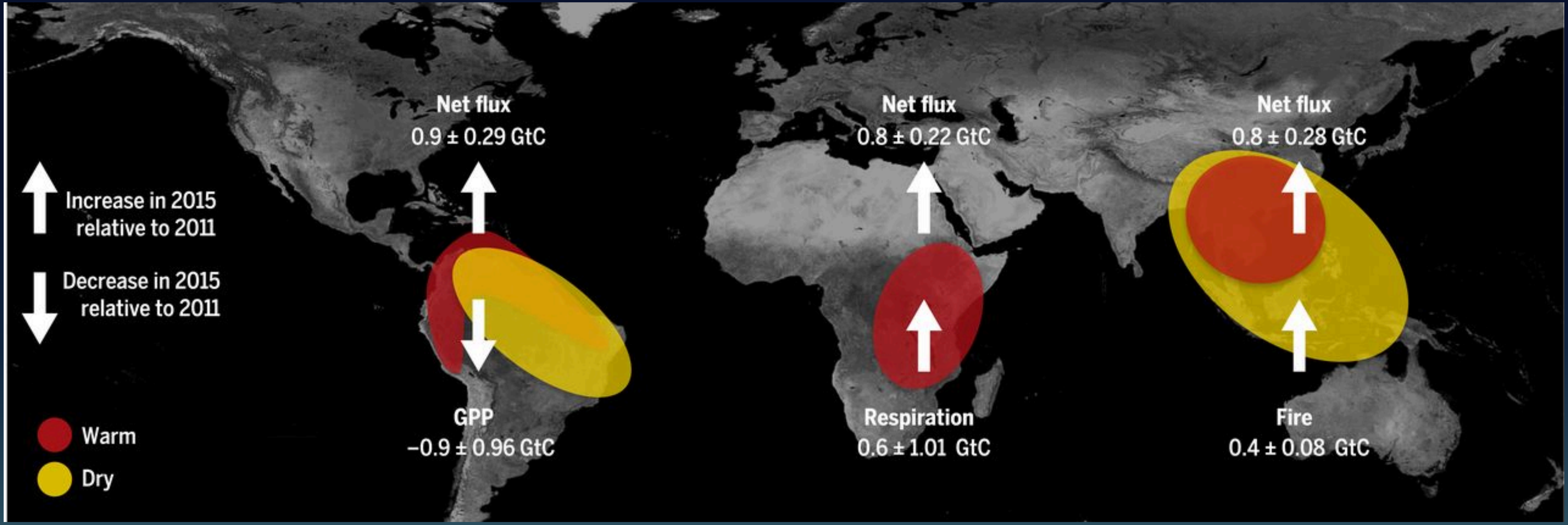
A complication, multiple paths, aerosol and other unspecified tenuous scatterers

$$I_\nu \sim I_{o\nu} R_\nu \exp[-L\tau_\nu(0, p_s) m]$$

An approximate model, with an uncertain model parameter *L*

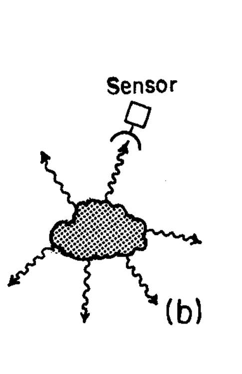
OCO now provides observations of naturally-driven variations of the carbon cycle

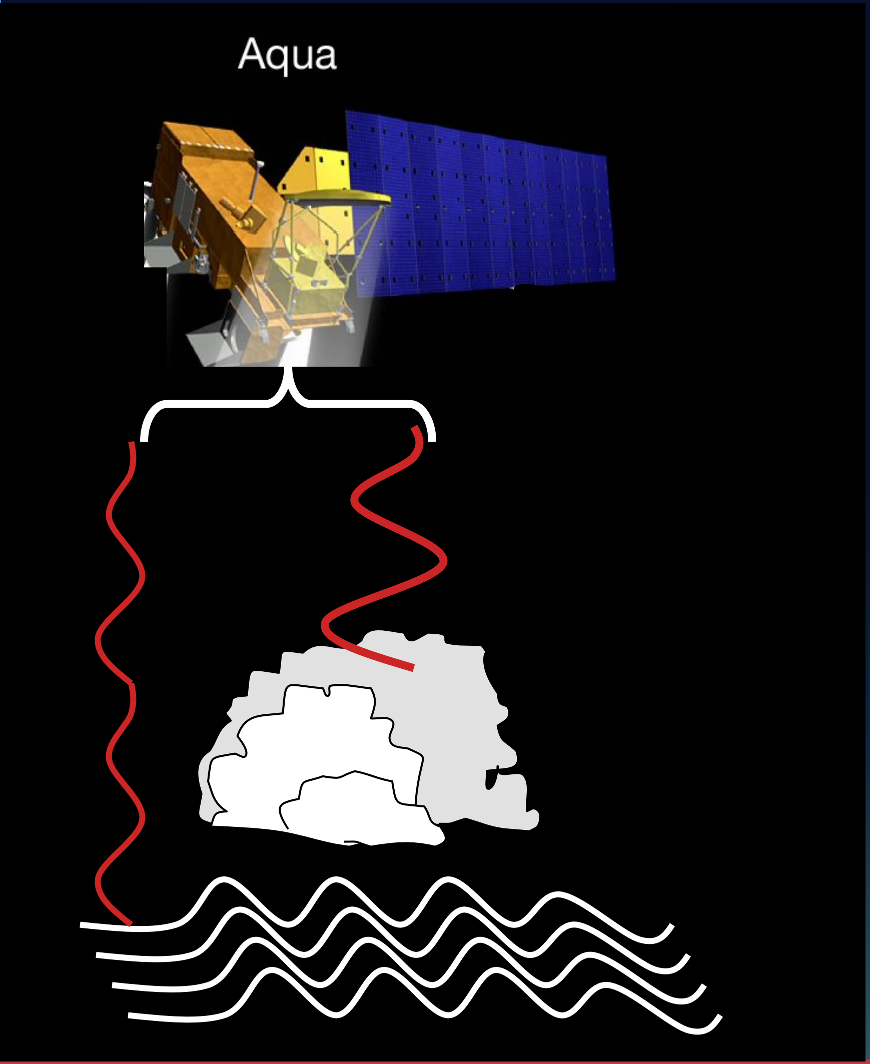
Impact of 2015/16 El Nino on ability of the terrestrial biosphere to take up carbon due to increasing temperature and decreasing rainfall



Liu et al, 2017

Emission - microwave radiance



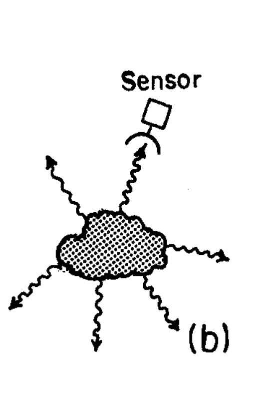


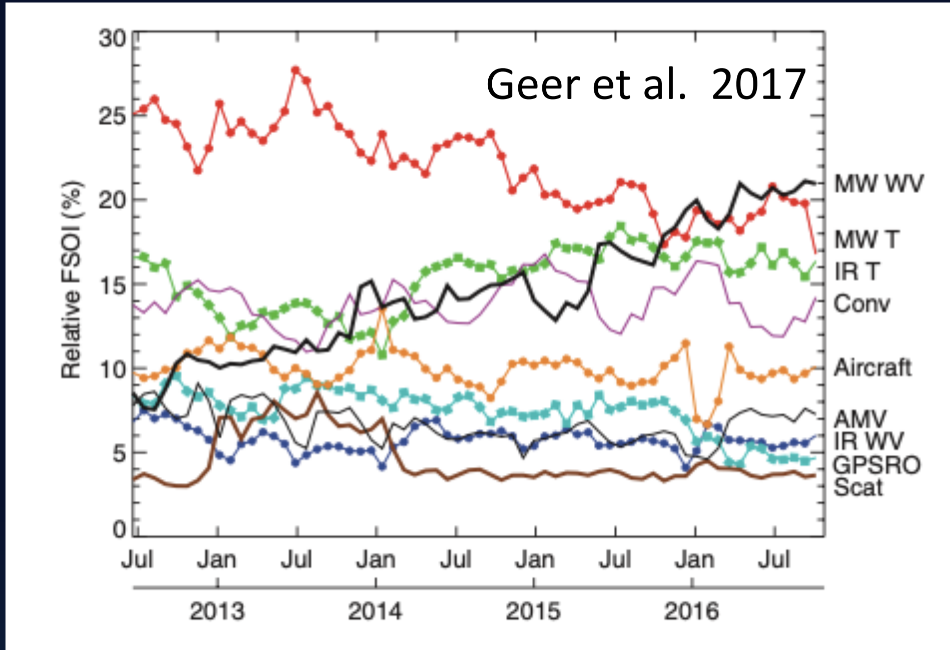
The difference is related to the absorbing - emitting species along the atmos path - mostly water vapor, cloud liquid water, and precipitation but other constituents

Current and Future Polar-Orbiting Microwave Radiometer Capabilities

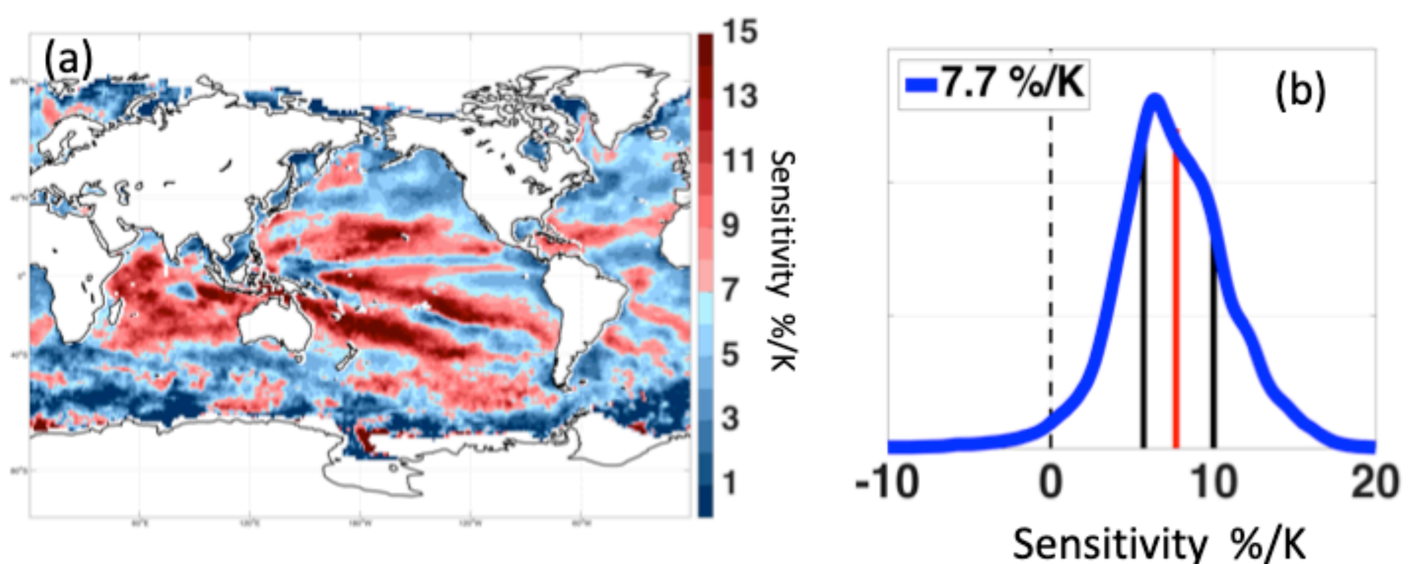
Satellite/Sensor	Useful for Observing			(First) Launch	Follow-on	Coverage until
	SST	Sea Ice Snow	Atmos.			
DMSP/SSMI/SSMIS		✓	✓	1987		?
WindSat	✓	✓	✓	2003		
FY-3/MWI	✓	✓	✓	2008	✓	2023
MeghaTropiques			✓	2011		
GCOM-W1/AMSR2	✓	✓	✓	2012		
GPM/GMI	✓		✓	2014		
OR-6/COWVR			✓	2018		
EPS-2G-B/MWI			✓	2022	✓	2040
WSF/MWI	?	?	?	2022	✓	?

SST = all-weather sea surface temperature Ocean fluxes, e.g. SeaFlux
Sea Ice & Snow = sea ice and snow-on-land cover
Atmos. = rain rate, columnar water vapor & cloud liquid water



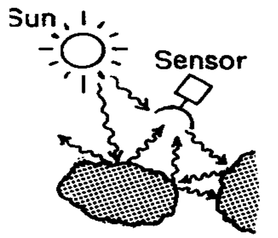


Between 2012 and 2016, the impact of microwave humidity, cloud and precipitation-sensitive observations ('MW WV' – ie cloudy radiances) has increased from 8% to 21% of the total observational impact.



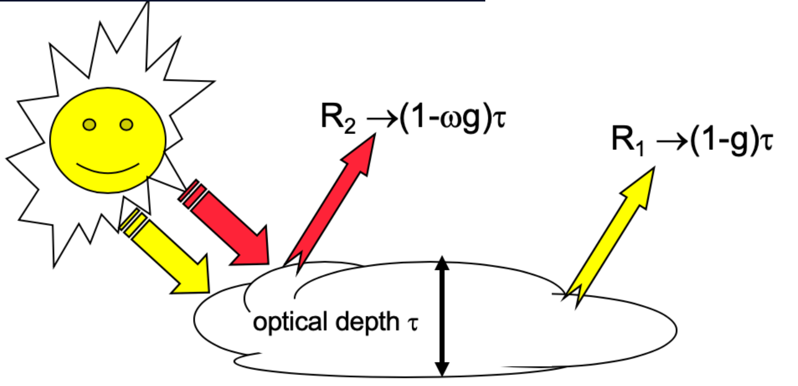
A microwave based 30 year climatology of cloud water, column water vapor, revealing change over time wrt temperature

Scattering: a passive example



Visible reflectance (R_1) is a function a combination of parameters, i.e. $R \rightarrow (1-g)\tau$

The reflection in the near-IR (R_2) is a function of optical depth τ and the scattering albedo ω- the latter is a function of particle size r_e.

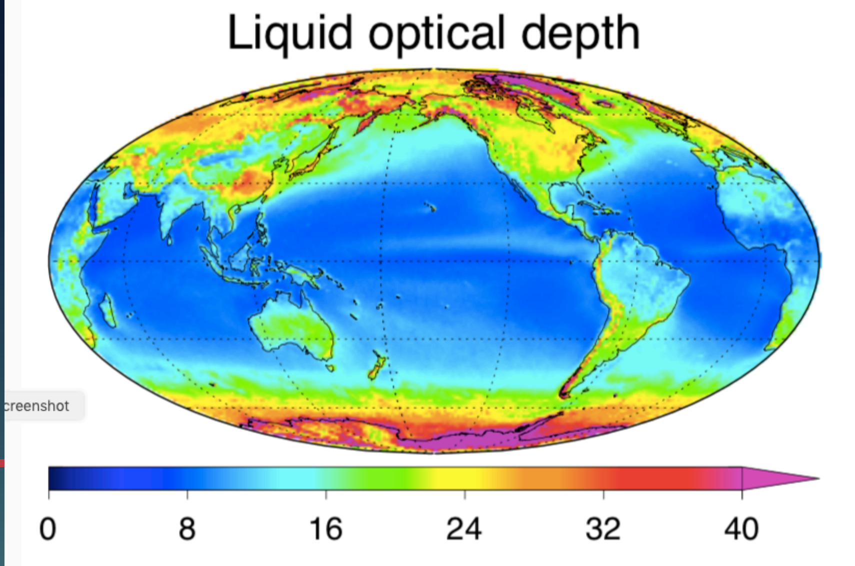


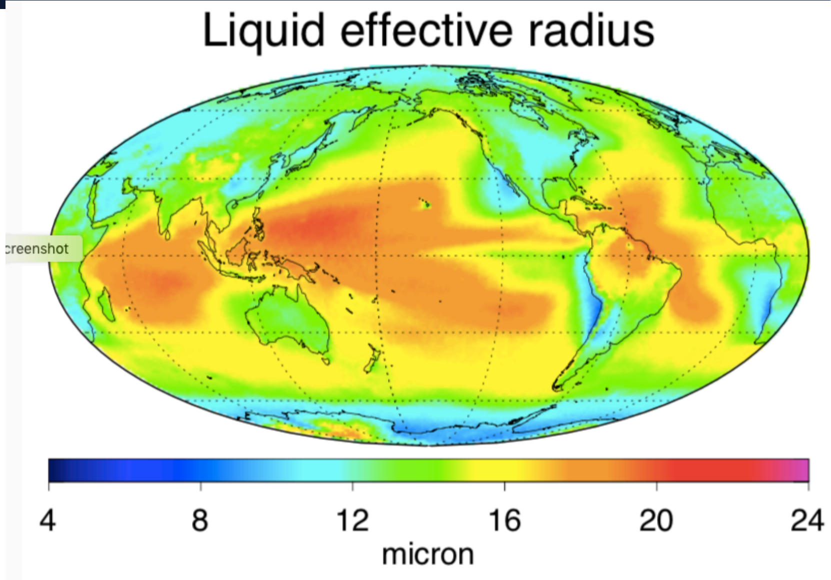
Measurements of reflection at two wavelengths (or spectral bands) returns the pair of parameters τ and r_e

$$\tau \rightarrow \frac{3}{3}\frac{LWP}{r_e}$$

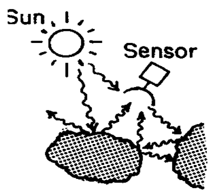
$$LWP \rightarrow \frac{2}{3}\tau r_e$$

15 year low cloud mean from MODIS



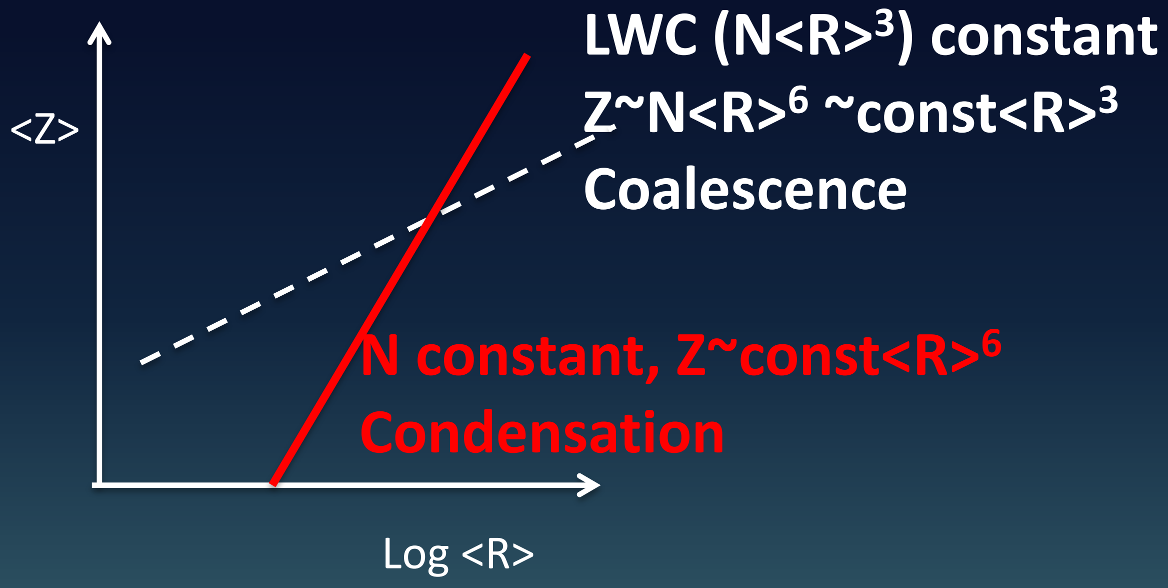


The power of integrated observations: particle growth regimes.



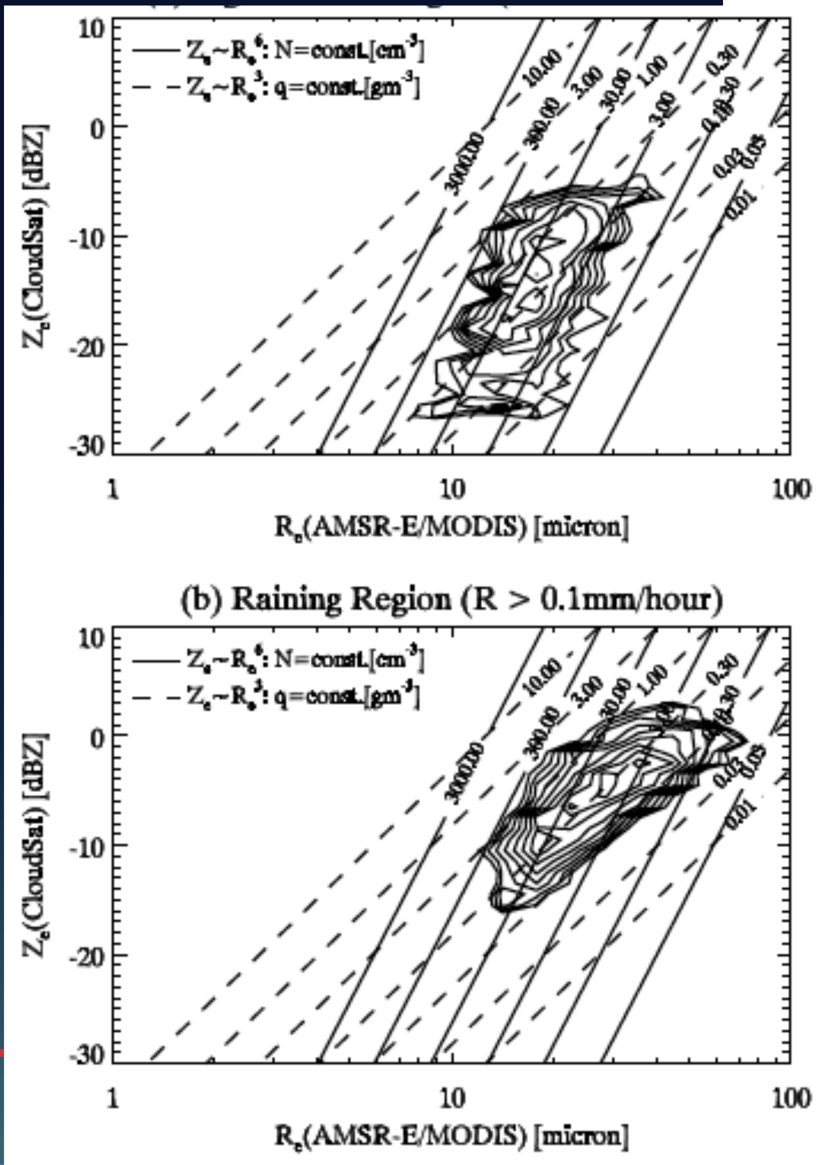
1) Microwave LWP*
2) Optical MODIS optical depth τ
3) Layer mean drop size <R>~ LWP/τ
4) Radar Layer mean <Z>

Suzuki et al., 2009

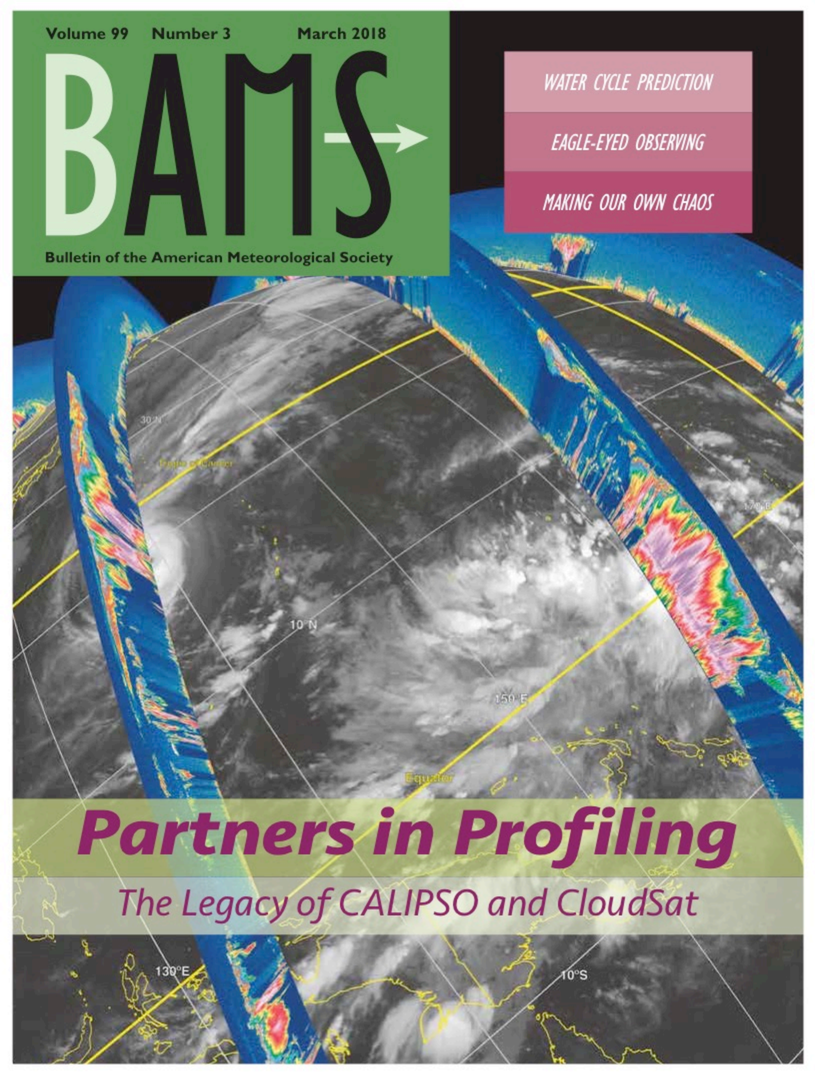


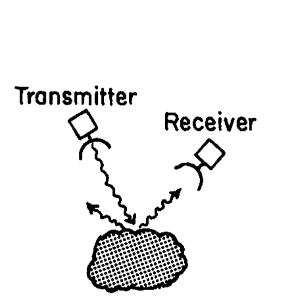
Cloud – condensation

Drizzle & Rain- colalescence



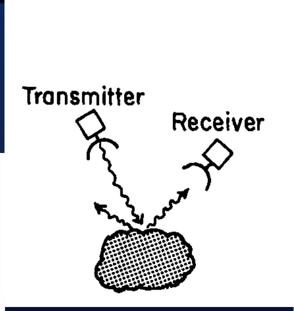
Active Sensing



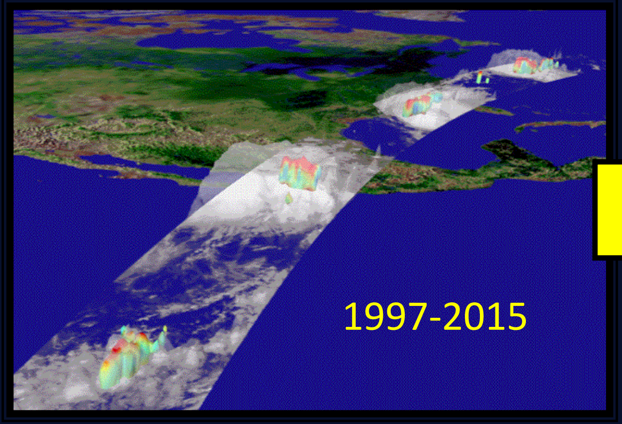


Perhaps the main advance is that active systems provide a much clearer idea of what it is we are looing at as we peer down on Earth. If exploited, This has the explicit effect of removing a main source of retrieval error - the crudeness of the 'atmospheric model'

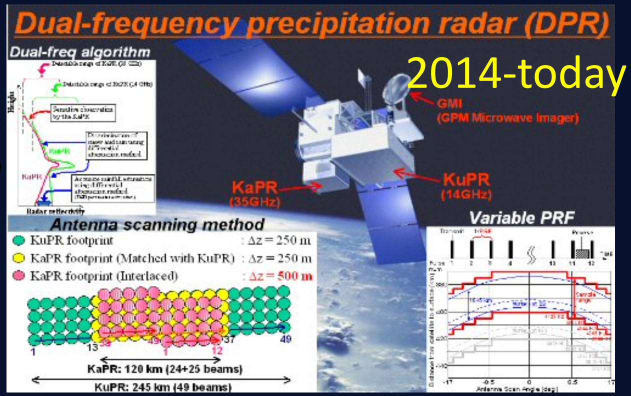
Active sensing from space - making major strides over the last 20 years

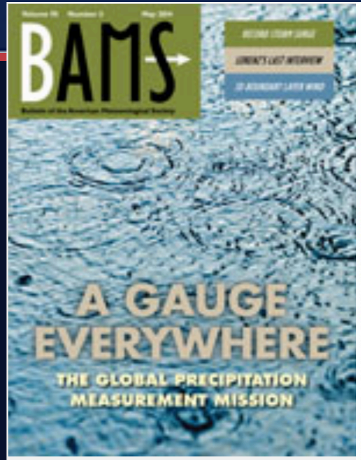


TRMM/PR – NICT/JAXA
Ku, Scanning , Tropical Rain

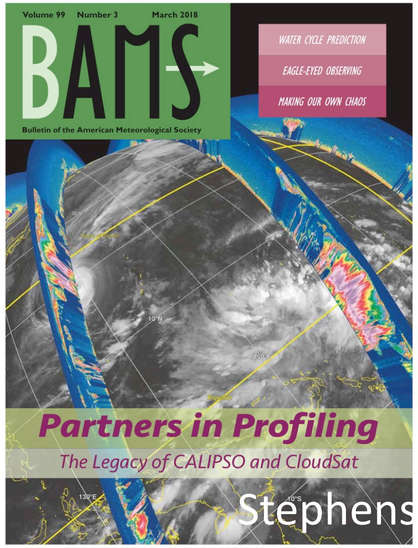


GPM/DPR – NICT/JAXA
Ku/Ka, Scanning, Precipitation



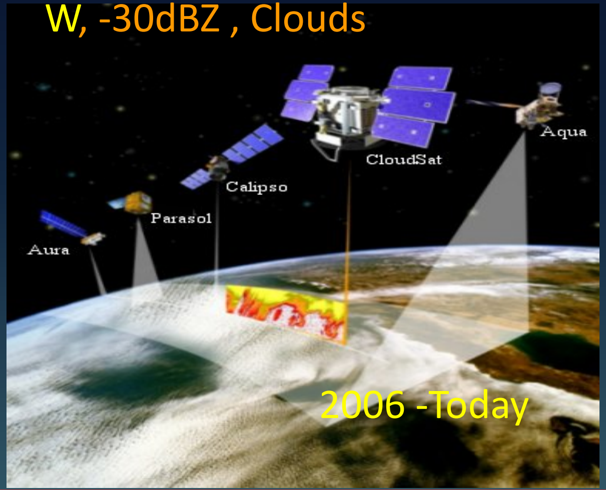


GPM
Hou et al., 2014
Skofronick-Jackson et al., 2017

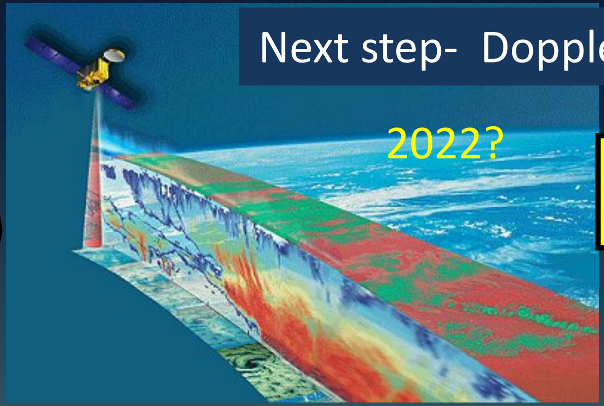


Stephens et al., 2018;
CloudSat and Calipso

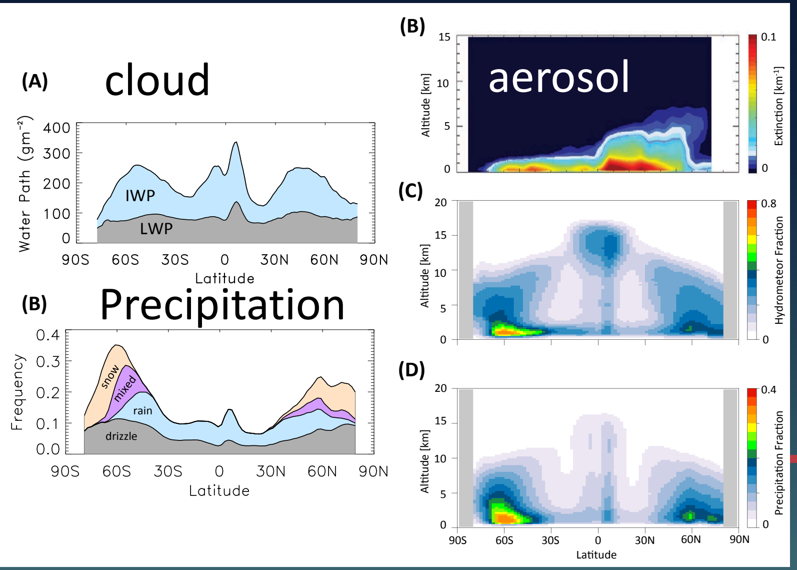
CloudSat/CPR – JPL/NASA
W, -30dBZ , Clouds



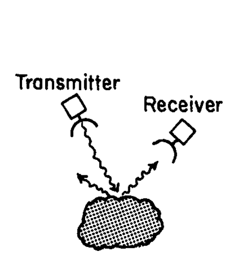
EarthCARE/CPR – NICT/JAXA
W, Doppler, Clouds



A-CCP

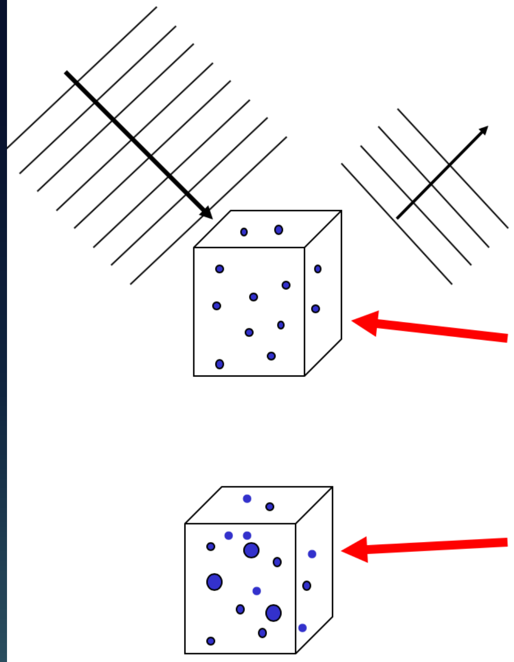


Radar Backscatter



Radar equation

$$P_r = C\frac{|K|^2}{r^2} Z \ \exp[-2\int_0^r \sigma_{ext}(r')dr']$$



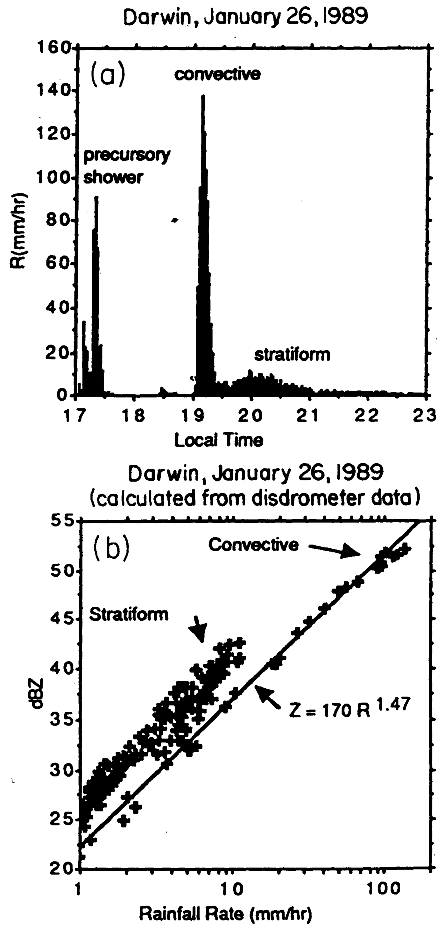
Power returned to radar after being scattered from cloud volume is related directly to size of particles in the volume

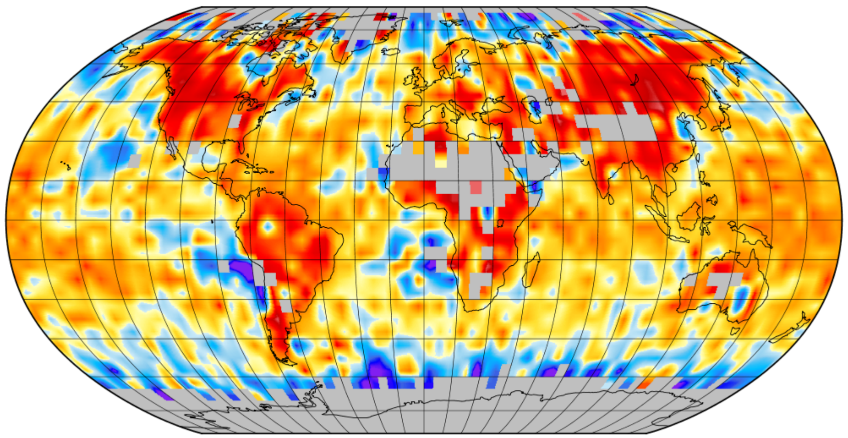
In atmospheric sciences, we express this returned power in terms of the quantity Z, the radar reflectivity

For a hypothetical cloud (particles all the same size), the power returned (or Z) is proportional to the square of the water and ice content (w) of the (radar) volume **$Z = aw^2$**

BUT

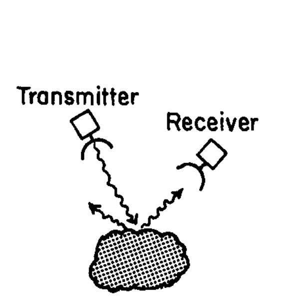
For real clouds, particles in the volume range in size. The power returned (i.e. Z) is *approximately* proportional to the square of the water and ice content of the (radar) volume. The degree to which this proportionality exists varies from cloud type to cloud type. **$Z \sim aw^b$**





Also Takahashi et al., 2017; QJRMS
Different nature of precipitation in shallow clouds over land cf oceans

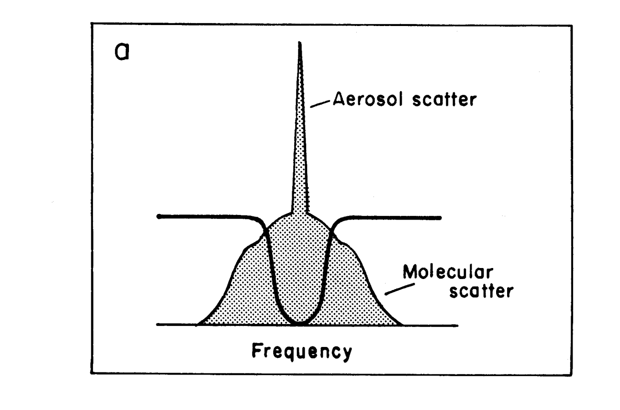
Lidar Backscatter (the present & the future)



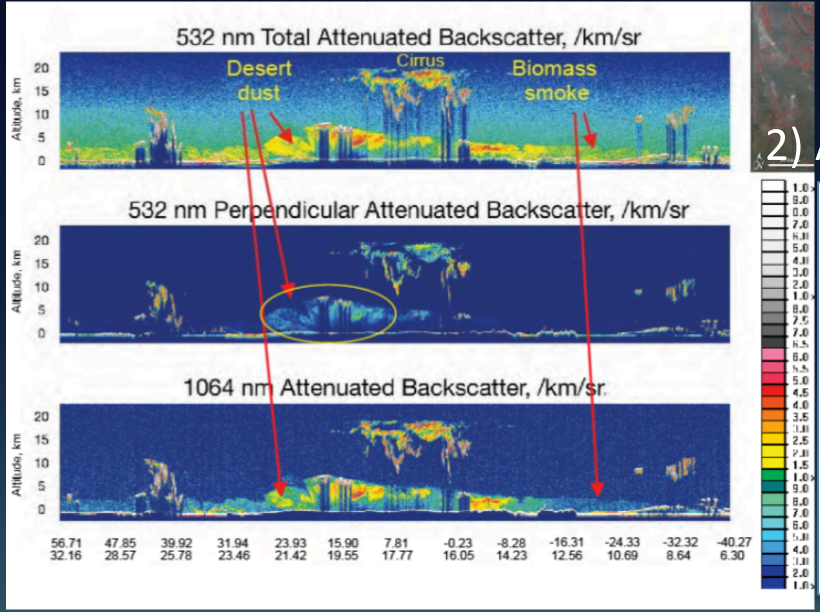
Lidar equation

$$P_r(R) = \frac{h}{2}\frac{C}{R^2}\frac{\beta(R)}{4\pi}\exp[-2\int_0^R \sigma_{ext}(r')dr']$$

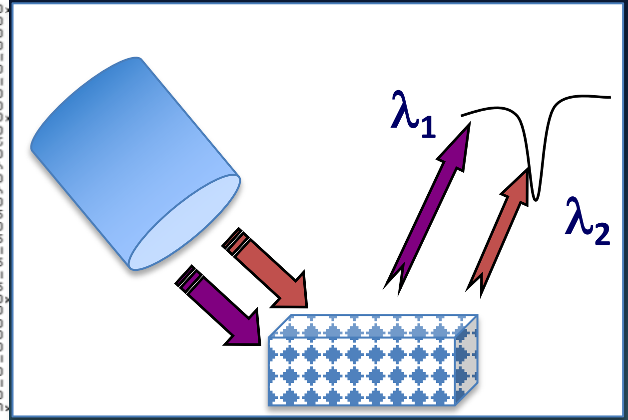
1) The Backscatter to extinction dilemma



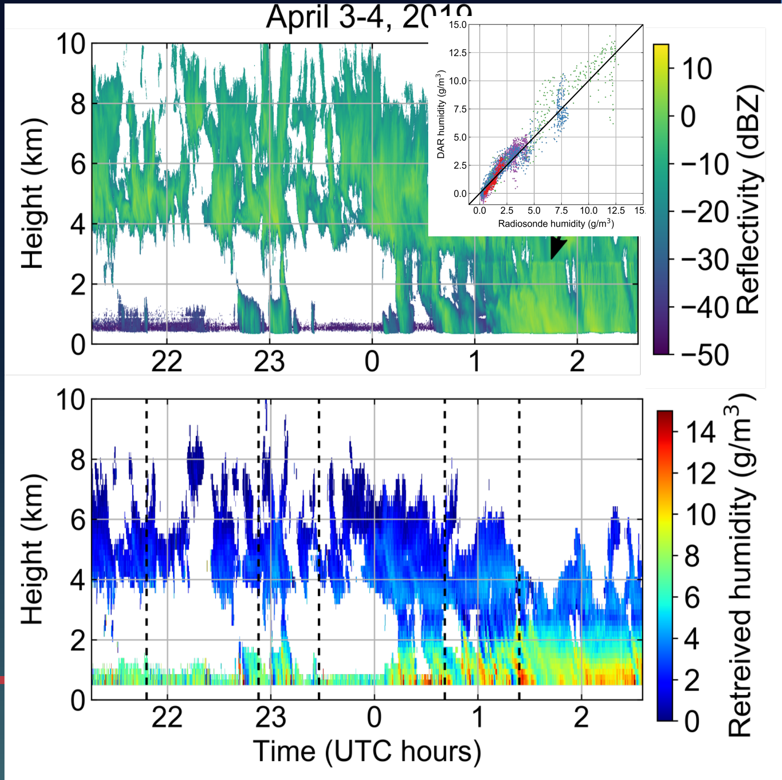
CALIPSO First light Backscatter , June 2006



2) Attenuated backscatter DIAL Lidar



Example of airborne DIA radar – in cloud humidity profiling
VIPR, Lebsock pers comm



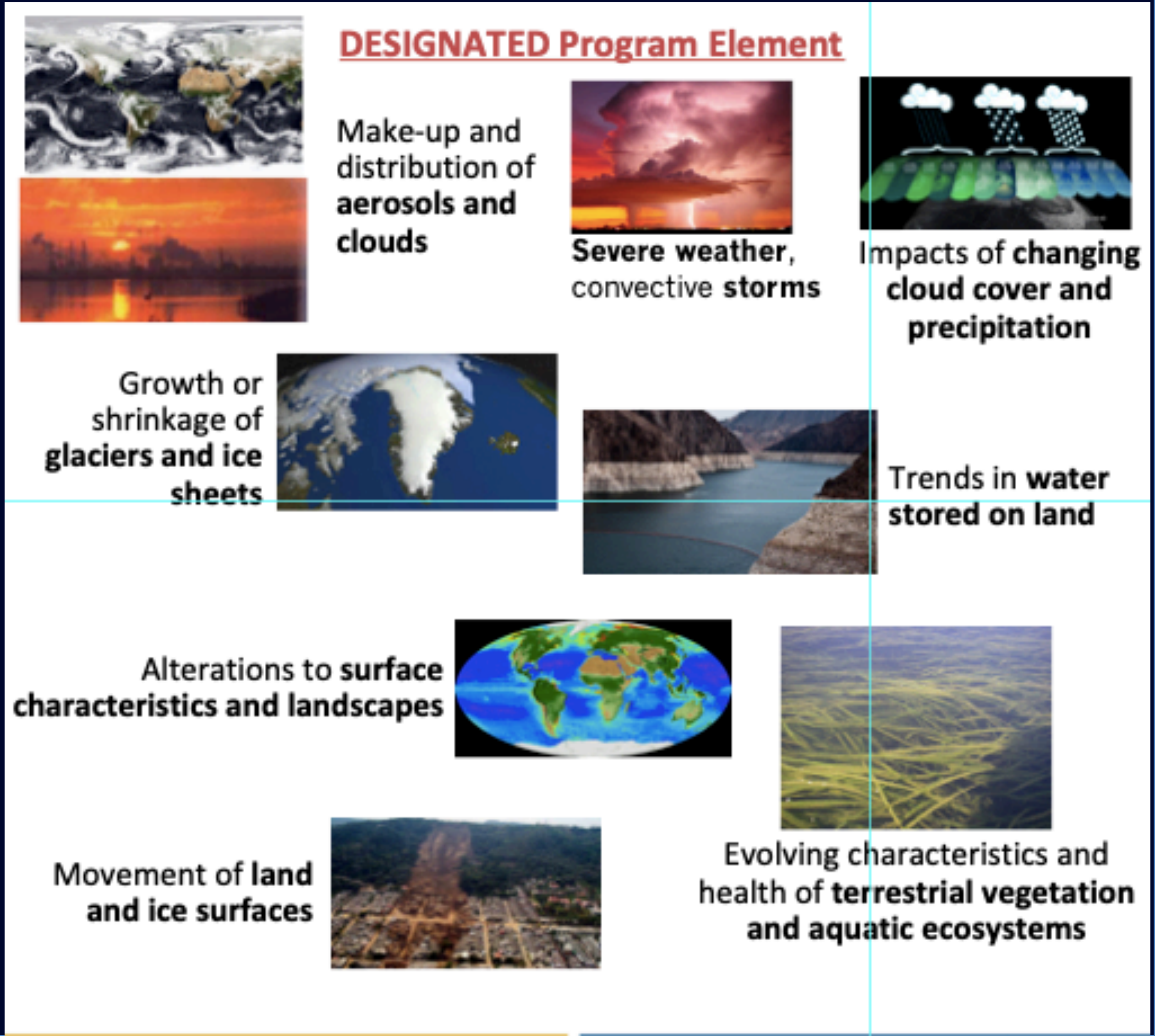
Some advances expected in the coming decade

1) ESAS2017-2027
2) Exploiting the PoR
3) The technology revolution

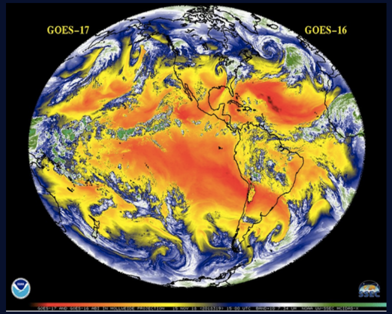
First designated observables under study

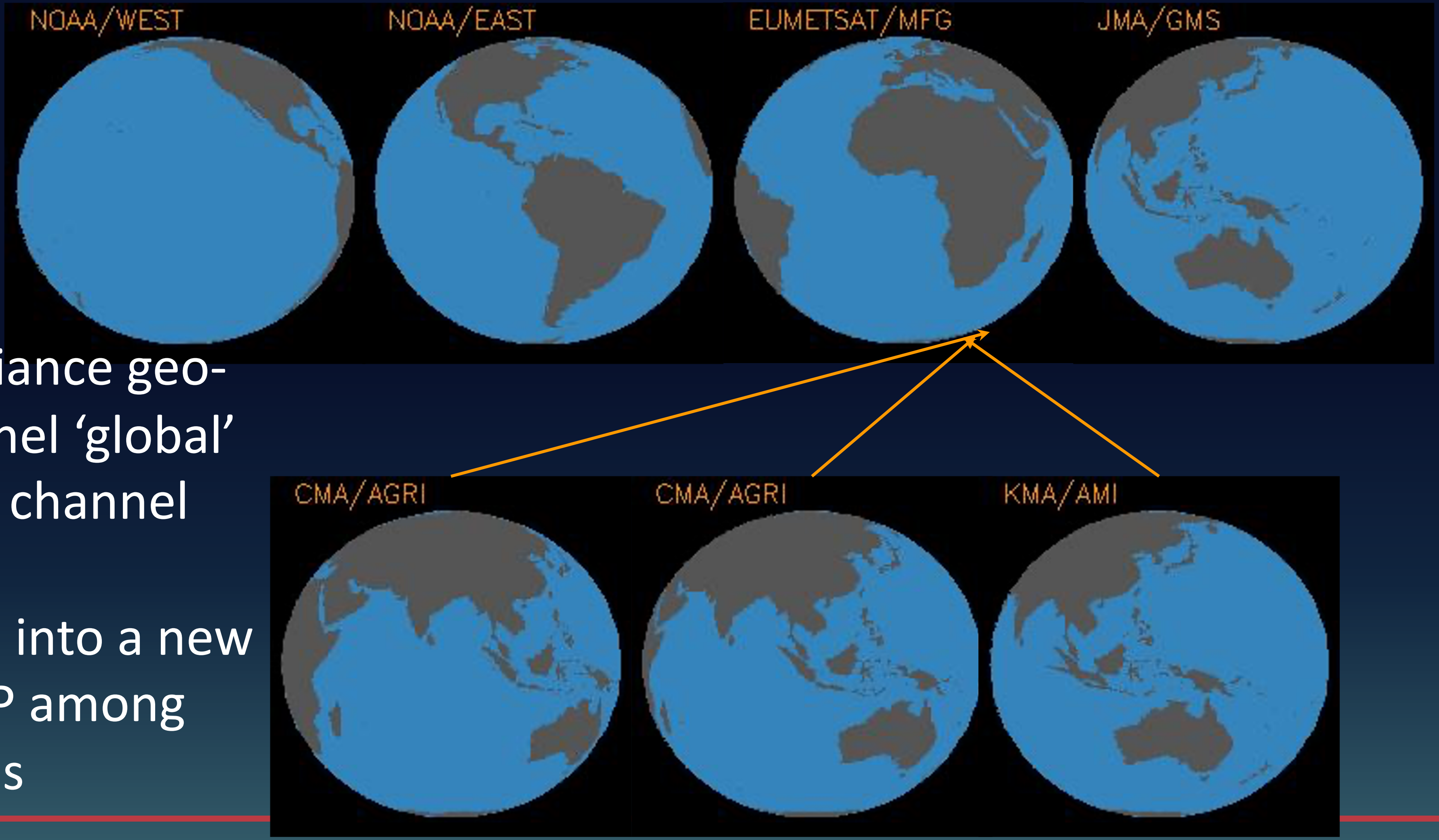
- SBG (surface biology and geology)
- A +CCP (aerosol + clouds, convection & precipitation – 'rebuilding the A-Train')

A-CCP Looking to include HSRL and Doppler – emphasis on movement in air (refer xxx, townhall yy tonight)



Exploiting geostationary advanced imagery – ISCCP next generation

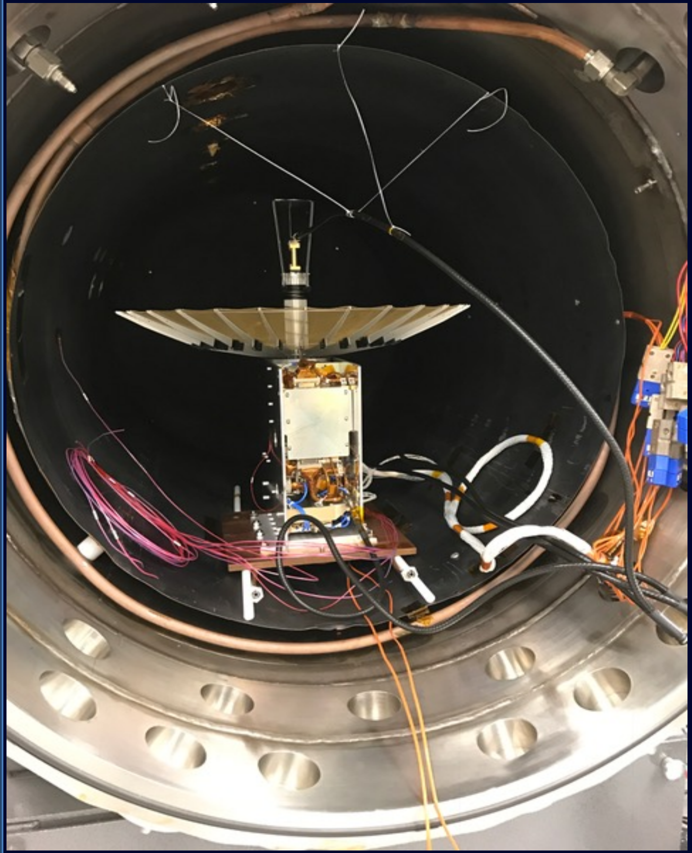




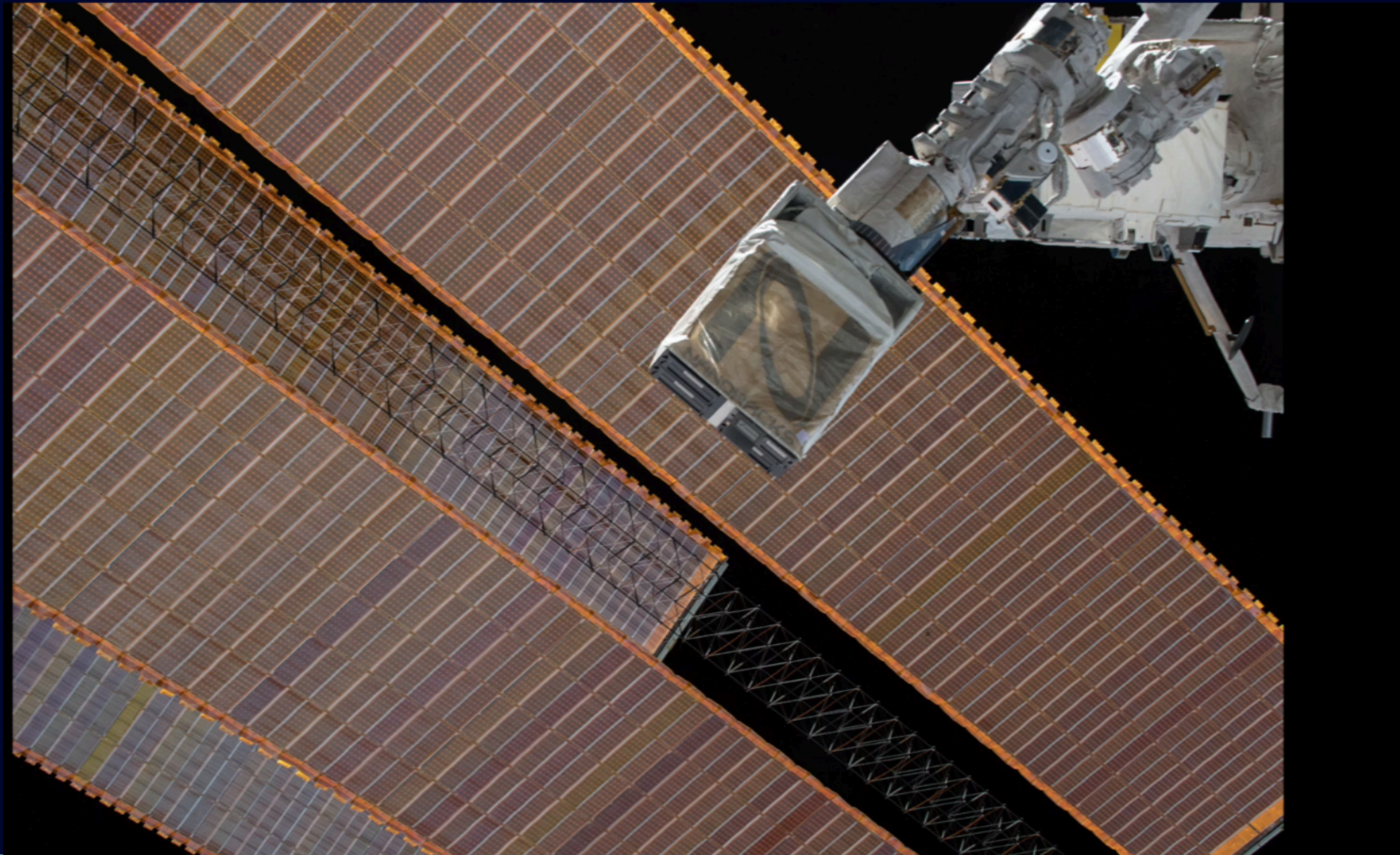
1) The spectral radiance geo-ring: multi-channel 'global' 2km, 10min ~10 channel

2) To be developed into a new generation ISCCP among *MANY* other uses

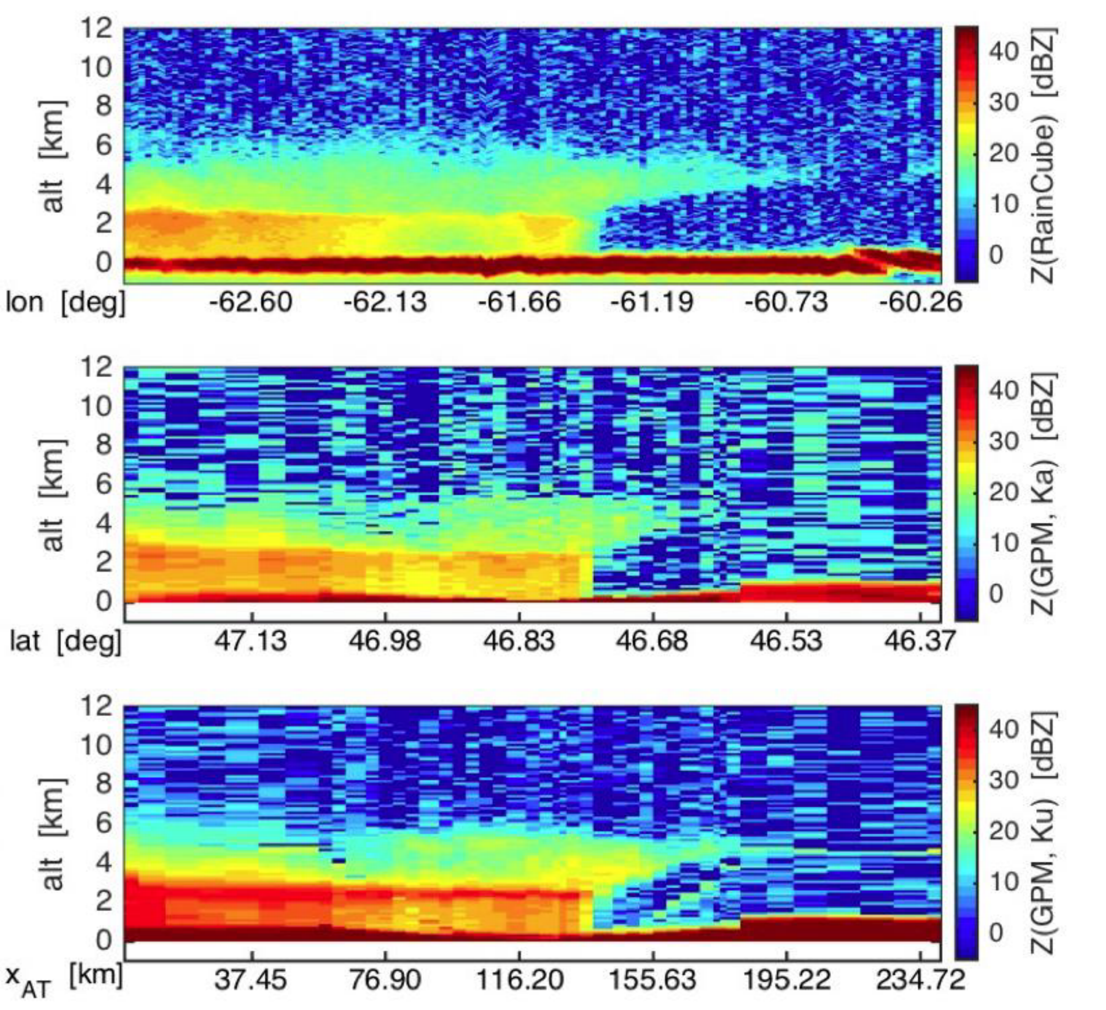
The ‘technology revolution’

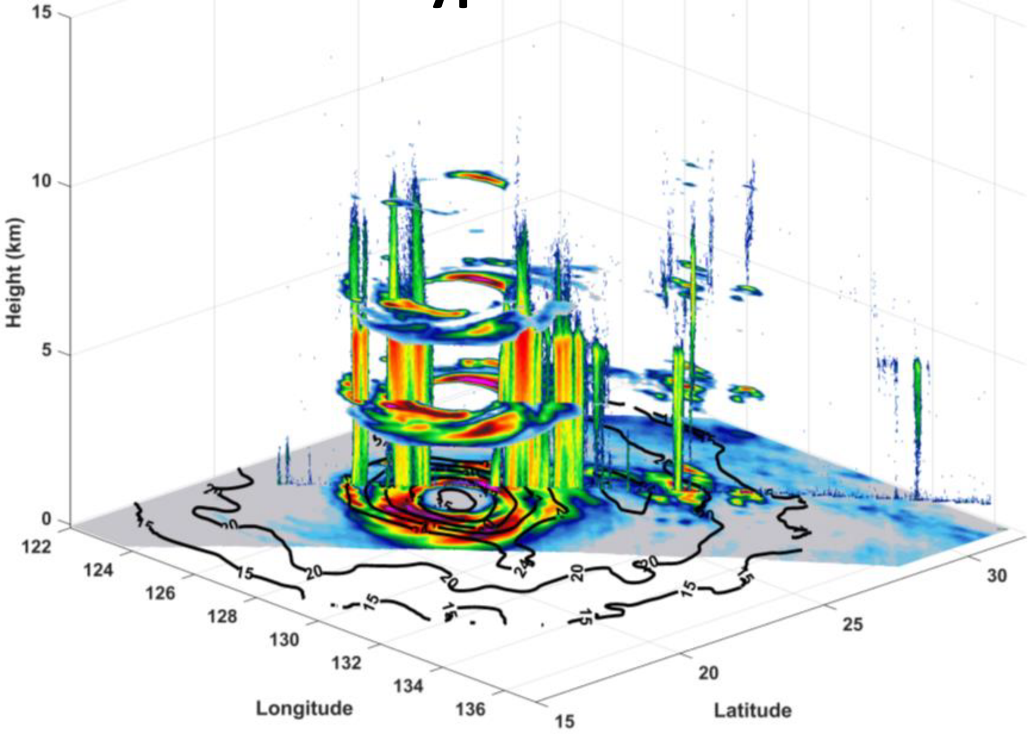


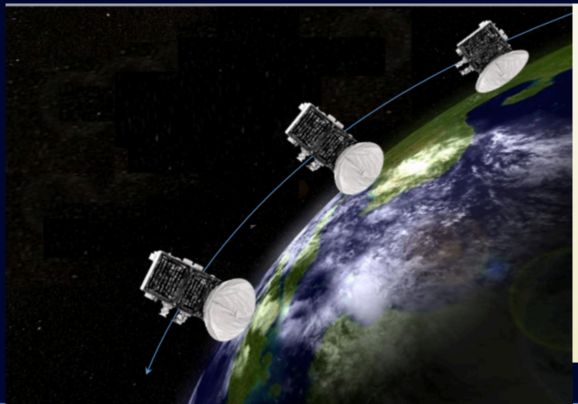
Stephens et al., 2019; The Emerging Technological Revolution in Earth Observations, *Bull.Amer.Met.Soc.* (to appear)

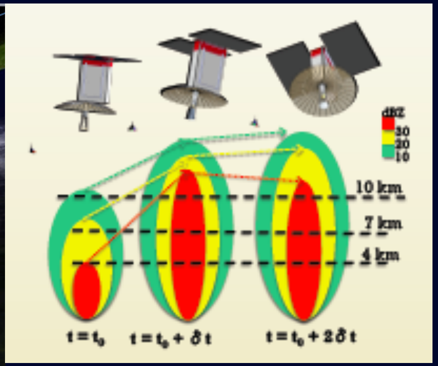


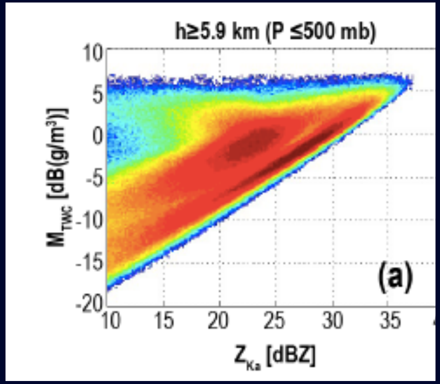
CYGNSS,TEMPEST & RainCube view of typhoon TRAMI

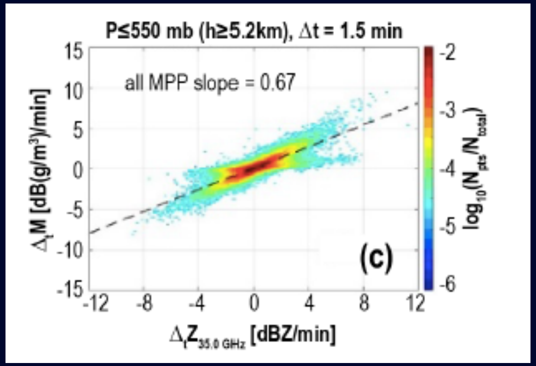












Summary

1) The performance of any given satellite remote sensing 'system' is complicated - the utility of the information critically depends on quantification of performance

2) We are now assembling relatively long records of information, both from operational and research systems - opening new directions of enquiry & understanding.

3) We have made significant progress in designing & using systems that combine different types of observations (and physics) –advancing measurement approaches significantly, opening new vistas on processes, and providing new ways to assess old methodologies

4) Technologies are rapidly advancing - offering new & 'affordable' ways to address science and application needs